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Modeling a Water Target with Proton Range and Target Density Coupling

T. Faugl[a,1], M. Stokely [b], B. Wieland [b], I. Bolotnov[a], J. Doster [a], J. Peeples [b], M. Poorman [b]

[a] North Carolina State University
[b] BTI Targetry, LLC

Introduction

Combined thermal and fluid modeling is useful for design and optimization of cyclotron water targets. Previous heat transfer models assumed either a distribution of void under saturation conditions [1] or a static volumetric heat distribution [2]. This work explores the coupling of Monte Carlo radiation transport and Computation Fluid Dynamics (CFD) software in a computational model of the BTI Targetry visualization target [3].

In a batch water target, as the target medium is heated by energy deposition from the proton beam, a non-uniform density distribution develops. Production target operation is ultimately limited by the range thickness of the target under conditions of reduced water density. Since proton range is a function of target density, the system model must include the corresponding change in the volumetric heat distribution. As an initial attempt to couple the radiation transport and fluid dynamics calculations, the scope of this work was limited to sub-cooled target conditions. With the increasing availability of multi-phase CFD capabilities, this work provides the basis for extending these calculations to boiling targets where the coupling of the radiation transport and fluid dynamics is expected to be much stronger.

Material and Methods

The Monte Carlo radiation transport code MCNPX was used to create energy deposition data tallies from proton interaction with the target water and beam window. The beam was modeled as a Gaussian distribution with 50% transmission through a 10 mm diameter collimator. The energy deposition tally was translated into a 3-dimensional, point-wise heat generation table and supplied as an input to the CFD code ANSYS CFX.

An iterative method was developed to couple the volumetric heat distribution from MCNPX to the fluid density distribution computed within ANSYS CFX. A 3-dimensional table of water density was exported from ANSYS CFX and imported into MCNPX. MCNPX was then used to calculate the heat generation rate (due to proton interactions) based on the assumed density profile. Applying the new heat generation profile to the ANSYS CFX model resulted in changes to the beam shape and penetration depth. The iterative scheme continued until converged values for density and heat generation rate were achieved.

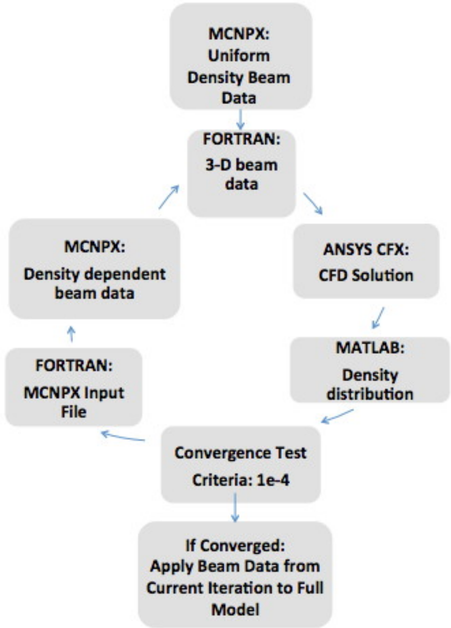

FIGURE 1. Iterative scheme flow chart

Monte Carlo methods are computationally expensive due to the large number of particle histories needed to generate accurate results. CFD simulations are also computationally expensive due to the large number of mesh elements needed. Optimization methods were used for both MCNPX and ANSYS CFX to result in achievable solution times and memory requirements. Local mesh refinement in the beam strike area was necessary for convergence. This was achieved by extending the boundary layer of the mesh within the target water domain deeper into the fluid. This allowed for better resolution within the beam strike area without significantly increasing the expense in the remainder of the fluid domain.

Additionally, direct simulation of the cooling water domain was decoupled from the computational model during the iterative process. Heat transfer coefficients from the first iteration were applied as a boundary condition for subsequent iterations. Once the beam and density distributions reached convergence, the

[1]Timothy Faugl, timothy.faugl@gmail.com

beam data was applied to a high fidelity "full" model, which included the cooling water domain as well as increased particle histories in MCNPX.

Results and Conclusions

The target was initially modeled assuming a 10 μA beam of 18 MeV protons into uniform density target water with operating pressure of 400 psi. These conditions resulted in predicted maximum temperatures below the saturation temperature.

The final converged beam data was compared to the original (uniform density) beam data. As expected, the density-dependent beam penetrates farther into the target water than when a uniform density is assumed. The density-dependent beam has a broader Bragg peak region with a lower maximum heat generation rate than the original beam. A line plot of the volumetric heat generation rate through the center of the beam is shown in Figure 2.

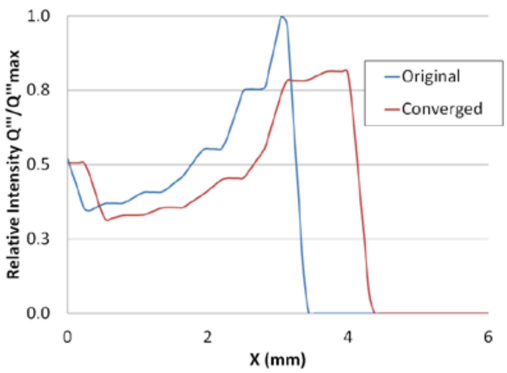

FIGURE 2. Relative intensity of centerline for original and converged beams

Even though the maximum volumetric heat generation rate was lower, the density-dependent beam resulted in a higher maximum fluid temperature.

TABLE 1. Summary of converged target results

	Original	Iterated
Beam Range (mm)	3.10	4.05
Max Q''' (W m^{-3})	1.73E+09	1.38E+09
Max. Temp. (°F)	362.77	383.34

Experiments were performed with the visualization target on an IBA 18/9 cyclotron, and video was recorded for a range of target operating conditions. Analysis of the video recordings from the experiment gives a peak fluid velocity in the target chamber of roughly 5-10 centimeters per second with a 10 μA beam current. The velocities predicted by the CFD model are within the same range. There is also good agreement between proton beam range between the experiment and model. The effective proton range can be seen in Figures 3 and 4.

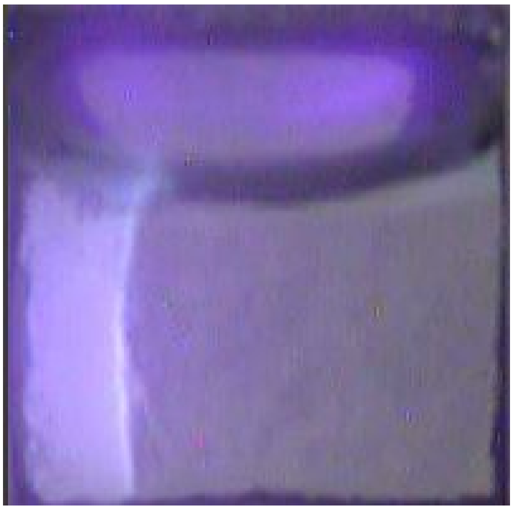

FIGURE 3. Experiment with subcooled conditions

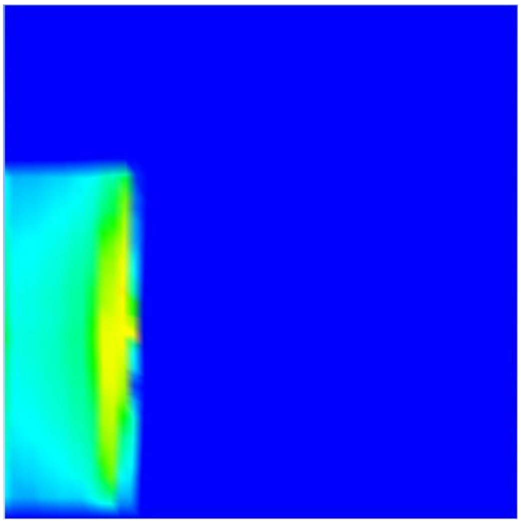

FIGURE 4. Converged heat input from CFD model

Future work will include applying the coupling technique for two-phase boiling conditions and to gas targets. If successful, this method should be a powerful tool for design and optimization of liquid and gas targets.

References

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[1]Timothy Faugl, timothy.faugl@gmail.com